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As the limits of long-range sonar are affected by ocean variability, the overarching goal of this work is to characterize, understand, and predict sound-speed variability in the upper ocean. Sound speed is a function of the ocean state variables temperature T, salinity S, which are themselves affected by such processes as stirring, mixing and internal waves. A long-range goal is thus the inversion of acoustic data to measure these processes.

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North Pacific Acoustic Laboratory – Underway CTD and SeaSoar Observations
Final Report

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LONG-TERM GOALS

As the limits of long-range sonar are affected by ocean variability, the overarching goal of this work is to characterize, understand, and predict sound-speed variability in the upper ocean. Sound speed is a function of the ocean state variables temperature *T*, salinity *S*, which are themselves affected by such processes as stirring, mixing and internal waves. A long-range goal is thus the inversion of acoustic data to measure these processes.

OBJECTIVES

Internal waves have long been considered the primary cause of acoustic energy fluctuations. However *T/S* variations at constant density, often called spice (Munk 1981), also affect sound speed. An objective of this work is to separate and quantify the effects of internal waves and spice on sound speed. The Garrett-Munk spectrum is an empirical characterization of internal waves that has withstood the test of time as a zero-order description. An equivalent statistical description of spice is an objective. Spice is strongly intermittent, and a description in terms only of power spectra may be inadequate, because it involves only the variance. An adequate characterization of spice may require higher order statistics, such as kurtosis, to describe intermittency. The mixed-layer base is especially important acoustically as the change in sound speed across it can be on the order of 10 m/s in a vertical distance of 10 m. Armed with realistic statistical descriptions of internal waves, spice, and the mixed-layer base, a final objective is numerical experimentation on acoustic propagation through oceans with realistic statistical properties.

APPROACH

The observational approach is to collect several realizations of a 1000-km section between acoustic moorings. A horizontal resolution of 10 km , and a vertical resolution of about 5 m is sufficient to identify and separate spice and internal waves. Two observational technologies have been used, Underway CTD and SeaSoar.

The Underway CTD (UCTD) is a newly developed device intended to profile from ships steaming as fast as 20 knots. The UCTD operates under the same principle as an XBT. By spooling tether line both

from the probe and a winch aboard ship, the velocity of the line through the water is zero, line drag is negligible and the probe can get arbitrarily deep. In contrast to an expendable, the UCTD is recovered as it is tethered by strong Spectra line. Profiles were made to 400 m every 30 min while riding along on the Spice04 acoustic mooring deployment cruise (chief scientist P. Worcester) in May-June 2004, yielding resolution of about 10 km at typical research vessel speeds of 10-12 knots. Another UCTD section was collected during the September-October 2004 LOAPEX cruise (chief scientist J. Mercer).

The development and construction of UCTD has been accomplished at SIO with the participation of several individuals. Specialist J. Klinke has responsibilities in several areas of UCTD mechanical and electrical design, construction, and operation. The Instrument Development Group (including engineers L. Regier and J. Dufour) has designed many of the components of the UCTD system. Graduate student B. Hodges has been involved in many stages of the development, testing, and use of UCTD.

The collection of UCTD data during NPAL has been a collaborative effort with J. Colosi (WHOI). During the Spice04 cruise, we trained Colosi and grad student J. Xu in the use of UCTD. For the LOAPEX cruise, we supplied UCTD equipment for Colosi to operate.

A cruise using SeaSoar was carried out in March-April 2005. SeaSoar is a standard oceanographic instrument towed at a speed of 8 knots, and capable of profiling to as deep as 400 m with a cycle distance of about 3 km. The combination of UCTD and SeaSoar sections has provided the data needed to evaluate the effect of spice on acoustic propagation. In addition to J. Klinke and B. Hodges, crew included postdoc S. Johnston and visiting French graduate student A. Despres. Operational support for the SeaSoar was provided by SIO Shipboard Technical Services, under a group led by C. Mattson.

In a collaboration with Walter Munk, we have examined the effect of the wavy mixed-layer base on acoustic propagation using a Monte Carlo approach wherein many acoustic rays are simulated, yielding statistics on such properties as ray inclination, range, travel time, and lower turning point.

WORK COMPLETED

A major thrust has been to quantify the effect of spice and internal waves on acoustics through numerical experimentation on realistic spice and internal-wave fields. A manuscript on sound propagation through spice and internal waves was published in September 2004 (Dzieciuch et al. 2004). The manuscript puts forth a method for separating spice and internal waves in SeaSoar data, and then uses a numerical model to examine acoustic propagation through oceans with either spice and/or internal waves filtered.

We have produced two statistical models for horizontal profiles of spice in the mixed layer. The first model has a spectrum whose slope and magnitude is empirically determined, equivalent to a Garrett-Munk-style model for spice. If spice variance were the only statistic relevant to acoustic propagation, then this simple model would be sufficient. But spice is highly intermittent, and rare, large gradients may be disproportionate acoustic scatterers. Our second statistical model reproduces a spice field with an empirical spectrum and probability density distribution, so intermittence is more faithfully reproduced. This model uses an iterative amplitude adjusted Fourier transform method (Schreiber and Schmitz 2000) to produce realization of the sound speed fields.

Important achievements of the first two years of this project included two successful cruises including UCTD measurements. First was the Spice04 mooring deployment cruise, during which over 160 UCTD casts were completed. The core UCTD measurements during the cruise were taken during two one-day transits between acoustic moorings. The transits covered 1000 km at speeds of 10-13 knots, and we made 97 UCTD casts. Casts were separated by approximately 30 min in time and 10 km in distance. All except one of the casts returned complete data. The LOAPEX cruise was the first use of UCTD by operators other than the developers. This "beta test" was successful as over 170 UCTD casts were completed.

A manuscript on the UCTD, based primarily on data from NPAL, is in press in the Journal of Atmospheric and Oceanic Technology (Rudnick and Klinke 2007). This manuscript is intended to be the definitive publication on the development of UCTD.

The SeaSoar cruise was undertaken to quantify hydrography in the upper 400 m along the 1000-km section defined by the three Spice04 acoustic moorings. Four tows were completed: (1) a sawtooth tow nominally from the surface to 400 m; (2) a sawtooth tow, roughly from 50 m to 150 m, concentrating on the mixed-layer base (MLB) and deep chlorophyll maximum (DCM); (3) a horizontal tow along the 50 dbar isobar; (4) a sawtooth tow from the surface to 400 m. Data return was excellent, and the goal of characterizing sound speed variability was achieved.

Walter Munk and I completed a study addressing the effect of a wavy MLB, as observed, on acoustic propagation (Rudnick and Munk 2006). The manuscript is published in the Journal of the Acoustical Society of America. Results are summarized below.

SeaSoar data from this project contributed to a global study of the MLB (Johnston and Rudnick 2007), submitted to the Journal of Physical Oceanography.

RESULTS

To quote from the NPAL proposal: "*Shadow-zone arrivals* ... made with bottom-mounted SOSUS receivers ... seem to be both ubiquitous and robust. The cause of the extensive scattering into what would be expected to be a geometric shadow zone remains unknown." The fundamental proposition of our work of the past year is that multiple reflections of an acoustic ray off the MLB can account for penetration into the shadow zone. Each reflection will involve a change in reflected angle causing a random walk, and an increase in the variance of the reflected angle. The quantity of interest in Snell's law is the cosine of the reflected angle, so the increase in variance of reflected angle implies a decrease in the cosine, and therefore a deepening of the lower turning point.

The results are best summarized through a joint probability density function (pdf) of arrivals of acoustic rays at 1000 km after 20 reflections off the MLB (Figure 1). The pdf simulates the arrivals from an non-directional source located at the sound channel axis at 1000 m, with an MLB at 70 m. The black line is the time front from a flat MLB, and the color shading is the pdf. There is a tendency for the scattered arrivals (from a wavy MLB) to precede those expected in a range-independent ocean (from a flat MLB). Importantly, arrivals occur several hundred meters below the range-independent lower turning point.

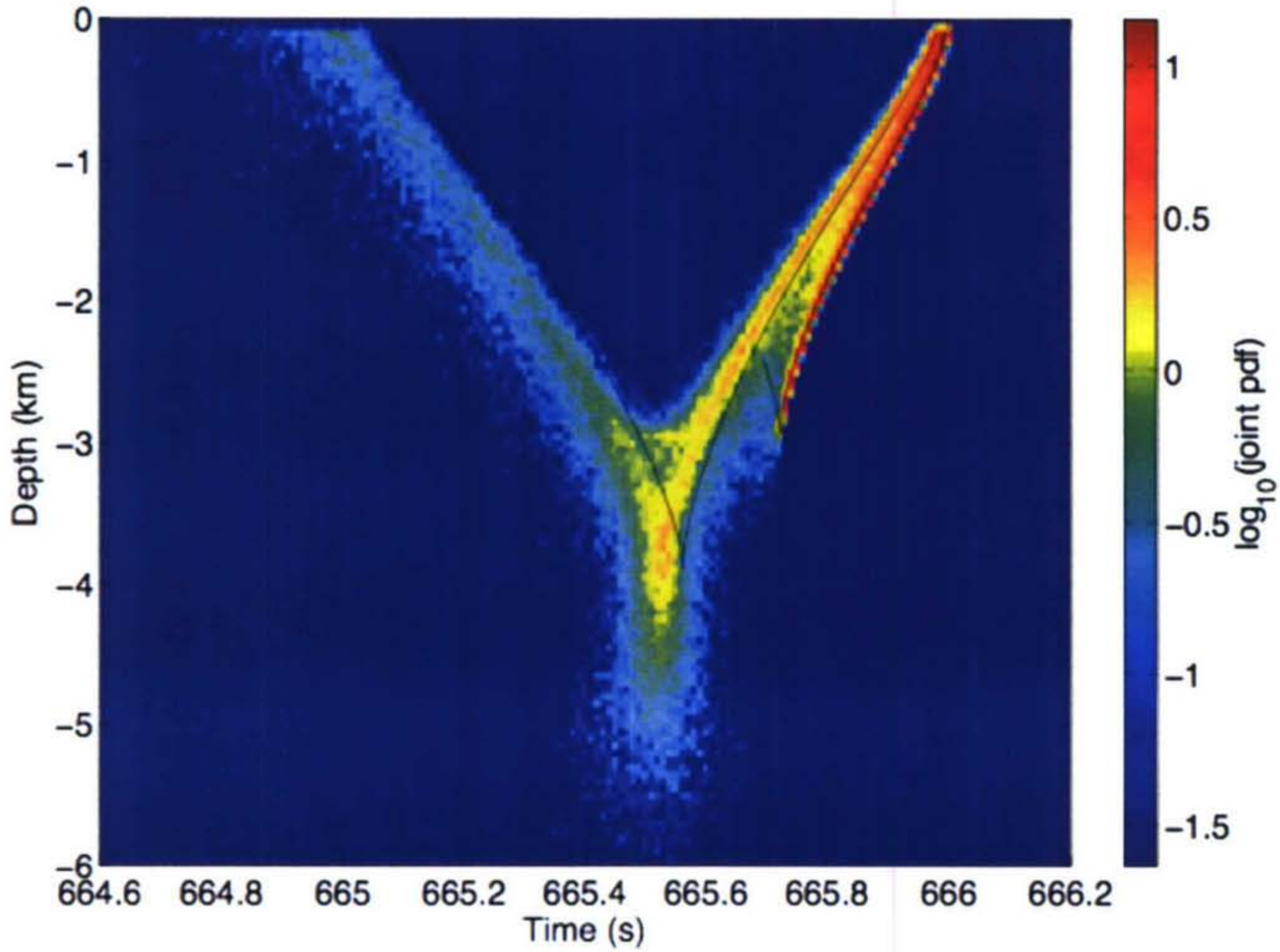

Figure 1. Joint probability density function of arrivals from a non-directional axial source at 1000-km range, after 20 reflections from the mixed-layer base. The black line is the time front in a range-independent ocean. The color shading is the arrival pdf.

Thus, scattering off the MLB is one possible explanation for early shadow zone arrivals. Later arrivals do not turn shallow enough to encounter the mixed layer, so the MLB cannot be implicated. However, a similar approach assuming repeated random refraction is capable of producing similar deepening for these later arrivals. Work is ongoing on the topic, with a goal of submitting a manuscript on the robustness of long range acoustic propagation.

IMPACT/APPLICATIONS

The statistical characterization of sound speed variability caused by spice promises an improved understanding of long-range acoustics propagation.

The UCTD provides a new method for rapid environmental measurement from any vessel at speeds up to 20 knots.

Acoustic reflection off the mixed-layer base provides a mechanism for the long-observed phenomenon of acoustic penetration into the deep shadow zone.

TRANSITIONS

UCTD is beginning to be built in the private sector, the probe by Sea-Bird, and the deck gear by OceanScience.

RELATED PROJECTS

This project is closely related to a number of ongoing projects focused on upper ocean variability as observed by SeaSoar, all of which are supported by NSF. The development of the Underway CTD has been supported by NOAA.

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